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A LITERATURE REVIEW AND ASSESSMENT OF TOUCH INTERACTIVE DEVICES

Mary E. Dominessy

October 1989
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The objectives of this report were to present a thorough review and assessment of past and present touch interactive devices (TIDs). Through the assessment of the different TIDs, a summary table of advantages and disadvantages and a features comparison chart was developed. The review also presents data gaps and research issues.

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fixed wire
pressure sensitive

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Mary E. Dominessy

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II. LITERATURE REVIEW AND ASSESSMENT OF TOUCH INTERACTIVE DEVICES

INTRODUCTION

Increased availability of computer systems has prompted the investigation of computer-operator interaction. Many different technologies have been developed to enable a computer operator to interact with computer-generated numerical and graphical data. Some of these technologies involve cursor control devices, such as keyboards, joysticks, trackballs, and "mice," while others employ a direct access approach, such as light pens, light guns, and touch interactive devices (TIDs). Direct access technology was first introduced in the early 1960s. Specifically, the TID concept was developed in 1967 by E. A. Johnson at the Royal Radar Establishment (RRE) in Malvern, United Kingdom (Johnson, 1967). Johnson was the first person to use the display plane as an interactive surface. He realized that using the natural mode of pointing would be very useful in optimizing person-machine interface and would consequently reduce operator reaction time. Ideally, TIDs provide a direct visual-to-tactile control and would decrease operator interaction time for many situations. They allow untrained users to run powerful software and complex data bases without requiring a working knowledge of the system. Touch interactive technologies generally are best used in menu selection hierarchies, and are not very well suited to entering alphanumeric data.

OBJECTIVES

The objectives of this report are to present an up-to-date review of literature which discusses TIDs, recognizes data gaps, and identifies research issues. The results will help develop a research program that will investigate the feasibility and limitations of TIDs in aviation applications.

TYPES OF TOUCH INTERACTIVE DEVICES

The technology for TIDs currently includes six main categories. Some of these categories include more than one design. Each category is discussed, and differences are briefly described.

Fixed Wire

The earliest TID is the touch wire, also known as the "Johnson Switch" (Schulze & Snyder, 1983). Johnson's design consists of a glass or transparent polyester-type material overlay with wires imbedded on the top surface. The original design consisted of four horizontal rows of wire with six fixed switch sites per row. Interaction is achieved by touching the wire switch with a finger. The location of the touch is determined by the imbalance in the capacitance bridge which results from the capacitance induced by the human body. Evolving from this design is the cross-wire TID which has two overlays, one with horizontal wires and the other with vertical wires. The wires on the two layers face each other, and when pressure is applied to a point of intersection, a return current path is registered and converted into an X,Y coordinate. The switch locations are fixed at each wire intersection.

Capacitive

These devices consist of a transparent conductive film deposited evenly on a glass overlay. A finger or conductive stylus activates the system by changing a small alternating signal that corresponds to the position on the film that is touched (Middo, Murdock, & Karnosh, 1987). This change in the electric signal is converted to an X,Y coordinate. Other capacitance-based devices operate using a discrete number of touch pads (electrodes). Each touch pad has an oscillating current. Touching a pad causes a change in the capacitance and alters the oscillating circuit frequency which the controller interprets as a signal (Logan, 1985). Again, the signal is converted to an X,Y coordinate.

Resistive Membrane

Resistive membrane TIDs all operate on a "sandwich" principle (see Figure 1) in which a touch is registered by the compression of a top plastic layer (usually mylar) against an underlying layer of plastic or glass (usually glass) (Logan, 1985). The adjacent mylar and glass surfaces are each coated with a conductive material and are separated by a grid of insulating clear plastic spacer dots. In operation, voltage is applied to the resistive layers in opposing directions X,Y. When touched, the layers are pressed together, and the resulting current and voltage are used to convert the touch position into X,Y coordinates.

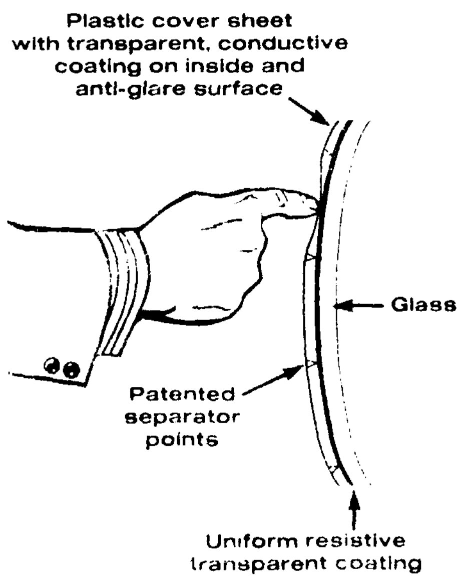

Figure 1. Resistive membrane touchscreen.

.ode (LED)

LED technology, first developed at the University of Illinois, involves infrared (IR) beam transmitters positioned along two perpendicular sides of a shadow box-like display frame. The other two sides of the frame have photocell receivers positioned so that each transmitter is paired to (directly across from) one receiver. In operation, IR beams traverse the display on the X and Y axes. When a finger or stylus breaks the matrix of light beams, at least two receptors (one X and one Y) do not receive the transmitted beams. The intersection point of these receptors is encoded as the X,Y touch position (Carroll, 1984).

Another optical touchscreen (see Figure 2) that projects an invisible plane of light just above the display uses an entirely different approach (Javetski, 1986). This design has a single LED on a motor mounted under one corner of the bezel. The motor continually sweeps the beam of light across a 90° arc that covers the display area. The combination of a mirror on one side of the bezel and retroreflectors on two adjacent sides of the bezel, causes the light beam to bounce back from two directions to a photodetector which is next to the light source. A touch is registered when beams from exactly two angles are interrupted. The controller determines the location of the touch by triangulation.

Surface Acoustic Wave (SAW)

Generally, the operational concept of SAW devices is similar to that of sonar. Most systems involve transducers mounted on at least two edges (some designs require all four) of the screen. Half of the transducers (one or two sides) transmit ultrasonic waves and the other half of the transducers, which are on opposing sides, act as receivers. A finger tip or stylus placed on the screen attenuates wave transmission on one or more paths, therefore revealing the position of the touch (Adler & Desmares, 1987).

Another approach discussed by Adler and Desmares using SAWs is the reflective array approach (see Figure 3). For this TID, one piezoelectric transducer is in the upper left corner and transmits a short burst of waves that travel horizontally along the top edge of the display. Along the path of these waves, an array of partial reflectors is positioned and spaced so as to create a constructive interface. The reflected waves traverse the panel vertically until the bottom row of waves that is reflected is an upside-down mirror image of the first row of waves. This last row of waves is moving in the direction of the receiving transducer in the bottom left corner of the display. The waves that are received have transmission times which are longer than those of the original burst of waves. When attenuation is introduced in the form of a touch, a "blip" appears in the output signal whose timing indicates the position of the touch.

The most recent development for an acoustic system is the Z-axis sensing capability. Operationally, the system measures the amount of surface waves absorbed by a finger or soft stylus. Varying the amount of touch pressure varies the degree of signal absorbed, which generates Z-axis information. The signal absorption causes wave attenuation; the amount of wave attenuation is proportional to the pressure of the touch (Javetski, 1986). The Z-axis technology will allow different areas of the screen to require different pressure thresholds for activation. The software can reject too light touches or near touches in given critical areas or accept extremely light touches in frequently used locations (Middo, Murdock, & Karnosh, 1987).

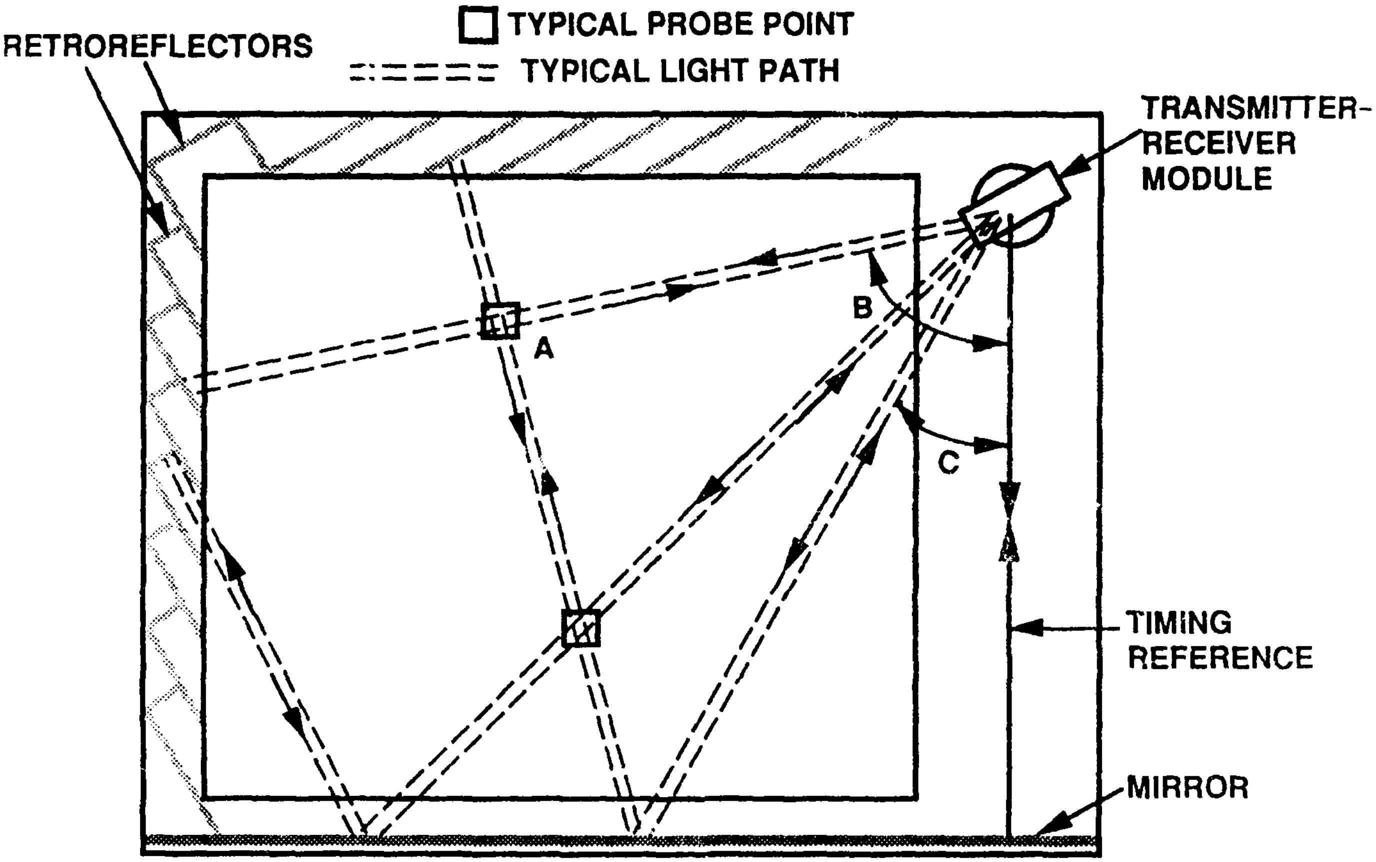

Figure 2. Optical touchscreen using single LED.

Note. When the ITW Entrex optical screen is touched at point A, the light that reaches the detector is blocked at two angles, B and C. This operation is made possible through the use of a mirror at the bottom of the screen and retroreflectors, which reflect light directly back upon itself on the top and left sides. A microprocessor determines the position of point A by triangulation.

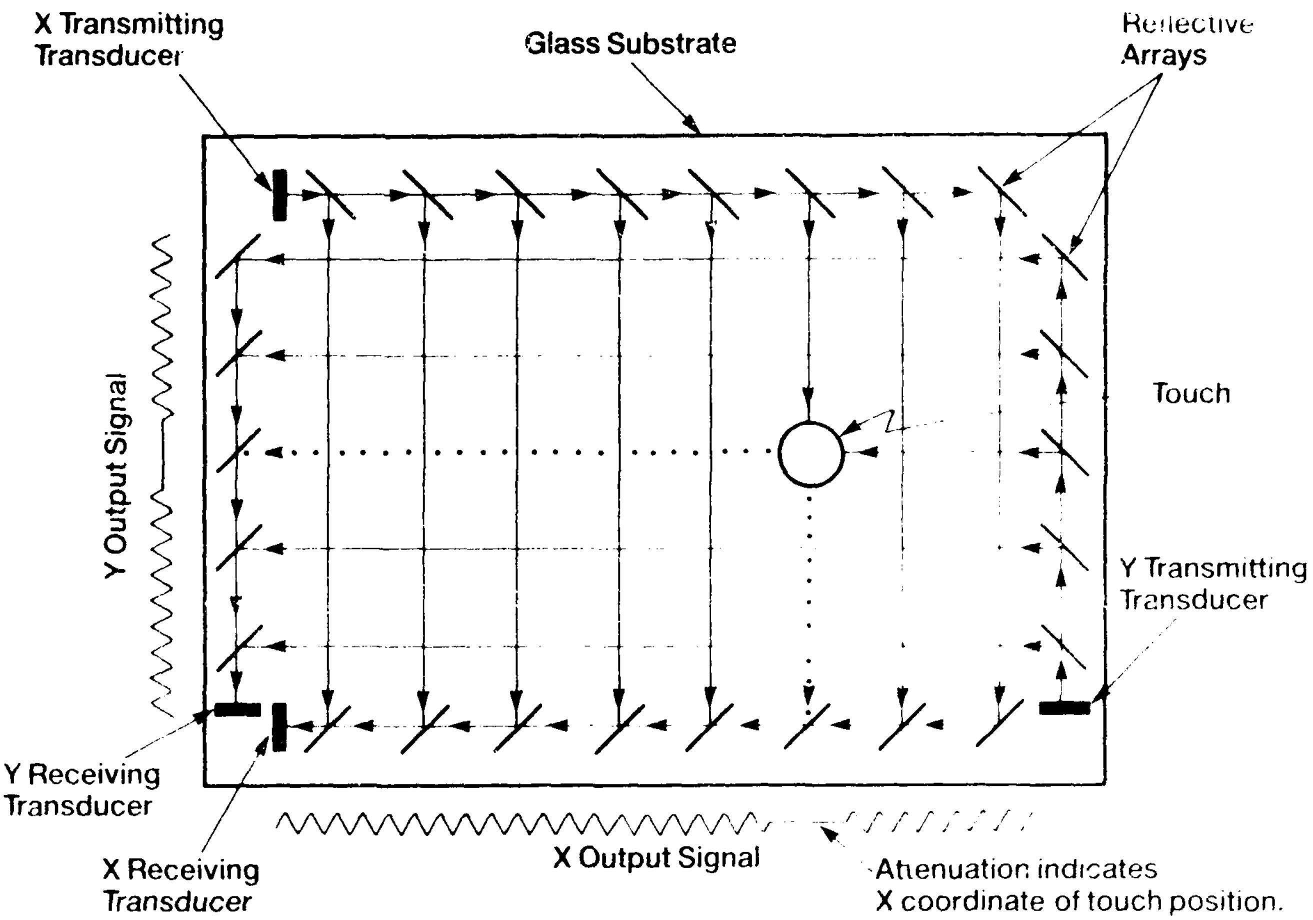

Figure 3. Surface acoustic wave--A breakthrough in touchscreen technology from Elographics.

Pressure-Sensitive Devices

This last category of TIDs includes a membrane-type overlay incorporating four pairs of strain gauges as the sensing mechanisms. The gauges are mounted between the display face and the overlay, one pair on each side mounted on rings at the center of each display edge. One strain gauge from each pair measures the force perpendicular to the overlay, while the other measures shear parallel to the overlay (Negroponte, Herot, & Weinzapfel, 1978). In operation, the output voltages of the strain gauges are electrically filtered and encoded into X,Y coordinates and codes for direction and acceleration of cursor movements. As with the sound acoustic wave devices, some pressure-sensitive devices use the Z dimension for sensing variations in touch pressure. Another type of pressure-sensitive TID, developed and marketed by IBM, consists of a chemically strengthened glass screen with a piezoelectric force transducer in each corner of the screen. When pressure is applied to the screen, a voltage is created and the voltage level is calculated at each transducer, and these values are compared to the reference values to determine the location of the touch. This system is compact and the touch sensitive screen is actually the screen for the computer display. The touch screen is not manufactured separately at this time and does not have Z-axis sensing capabilities.

IBM has investigated another type of pressure-sensitive touch screen overlay. According to an IBM Technical Disclosure Bulletin (1986), the system's overlay is constructed of transparent plastic with a continuously hollow channel embedded and built into it. The channel forms a tube that is filled with air or similar gas. Two pressure sensors, one at either end of the channel, detect the changes in pressure when a finger or other stylus is pressed against the overlay. The pressure waves, which are formed when the channel is collapsed by a touch, travel toward both ends of the channel and typically arrive at different times. The pressure sensors detect the changes in pressure and convert them to electric signals. The difference in arrival times, along with the knowledge of which pressure front arrived first, is used to calculate the location of the initializing action--the touch. The material for this device has elasticity and was specifically chosen to give the operator a switch action feel when pressing the screen. The tactile feel and the sensing resolution can be changed by using a gas other than air or by pressurizing the contents of the channel tube. Pressurized overlays may also be suitable for use in environments where atmospheric conditions vary, such as aircraft or spacecraft (IBM Technical Disclosure Bulletin, 1986).

OPERATIONAL CONSIDERATIONS FOR TIDs

Review of the literature indicates that numerous operational considerations should be acknowledged and controlled, if possible, when designing, selecting, or operating TIDs. These considerations all affect the operator interface with TIDs in some manner. The considerations cluster in two groups. The first group includes display and device considerations, and the second group includes work place or environmental considerations. Each group of considerations is discussed on the following pages.

Display and Device System Considerations

Parallax

Parallax is the apparent displacement of an object as seen from two different points not on a line with the object (see Figure 4). Parallax is a problem present to some degree in all touch systems caused by a combination of factors. The first contributor is the nonperpendicular line of sight of the operator to the display. Next, the finger or stylus approaches the screen at an angle different from the line of sight. Finally, displays typically have a curved surface and most TIDs work best on a flat plane. The result of these factors is, the place where the operator looks and where the touch activation occurs are not always the same point (Car[illegible], 1984).

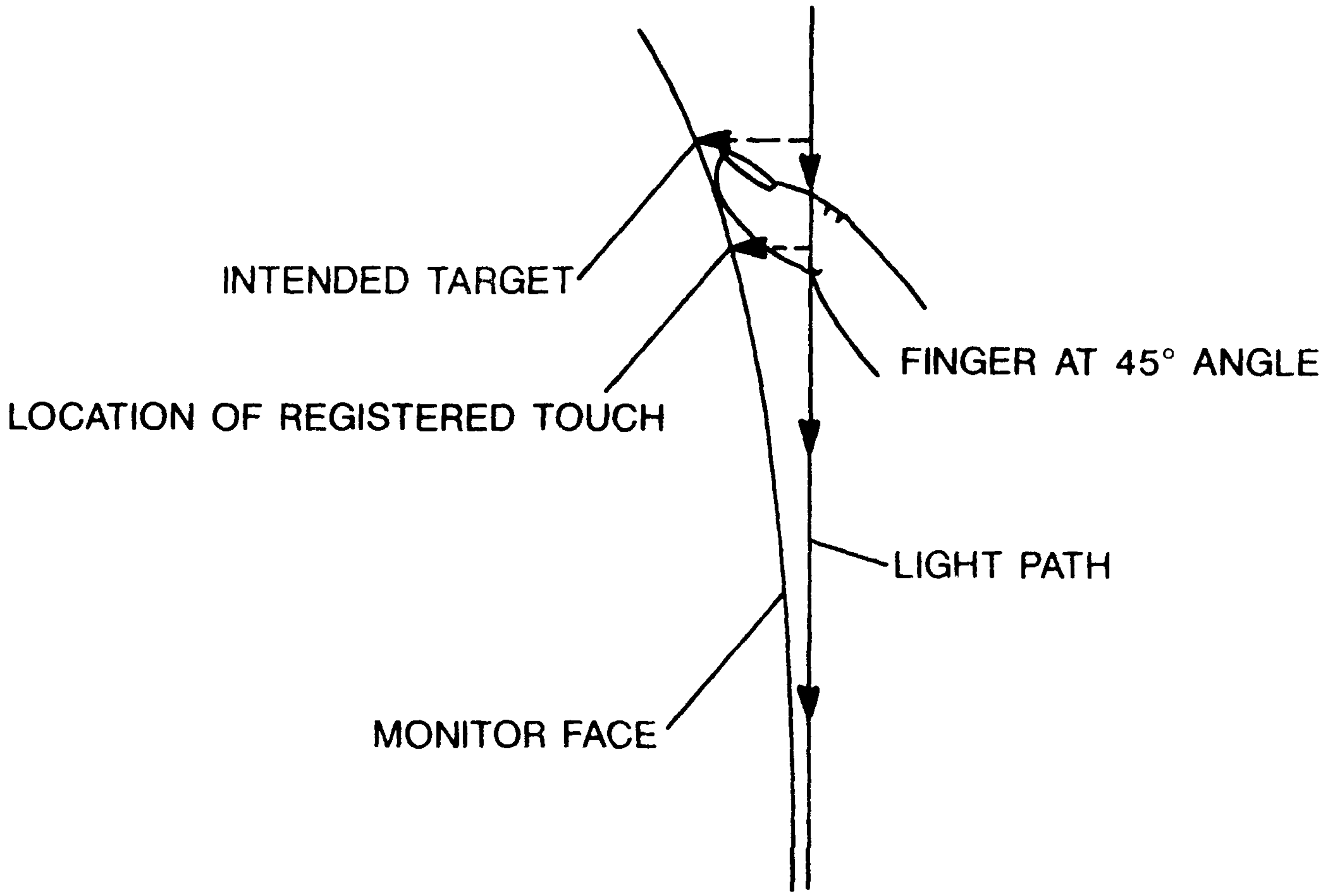

Figure 4. Parallax caused when optical touchscreen is used with curved displays.

Given the problem of parallax, many TID systems have been designed to minimize its effects. Overlay systems can experience some parallax, but if the overlays are shaped to match the curve of the display screen, parallax is nearly eliminated. Parallax is more noticeable in LED systems than in any other TID system. This has prompted the development of several procedures designed specifically to correct for parallax. Murer (cited in Pfauth & Priest, 1981) noted that some manufacturers recommend increasing the size of the touch area targets on the periphery of the screen or avoid using the edges of the screen where parallax is the worst. An attempt to reduce parallax is to approximate the spherical surface of the CRT by using two flat plane LED assemblies in both the vertical and horizontal planes angled so the CRT display surface is quartered. The designers of this system (Beairsto, Hastbacka, & Cawley, as cited in Pfauth & Priest, 1981) claim that this redesign permits all usable LED beams to be within 0.2 inch of the CRT surface, therefore reducing parallax. Another corrective procedure involves angled beam scanning systems in which the touch position is calculated by measuring the extent of the shadow it casts on two sides of the screen when illuminated by broad beam IR light from the other two sides. The last procedure discussed in Carroll (1984) is a method that helps alleviate parallax by curving the rows of optical devices to match the screen's curvature.

Response Time and Feedback

The response time and feedback capabilities of a touch system are critical for user acceptance of the system. When a TID is used for input control, the classical tactile feedback of button displacement or dial rotation is lost. Therefore, it is important to provide the operator with alternate forms of feedback. The distinction between system response and feedback can be confusing. Some experts argue that the system's response is the feedback. The following paragraphs show that in some instances this is true, but it need not always be the case.

The response time of a touch system is the time required to process a valid touch and return the results of that touch. The inherent response time of a TID is the time required for the device to detect and encode a touch. The system response time may vary, given the content of processing required. Several factors affect the response time of a system: sensor technology, processing speed, access to the host electronics, application software, and the nature of the application itself (Carroll, 1984). In most cases, the response time will be very fast (10 to 100 msec). It is imperative that the response to a touch be prompt so the user does not become bored and impatient. Even the slightest perceivable delay in system response may interfere with its natural feel. Furthermore, system delays can cause uncertainty, resulting in repeated or erroneous activation (Middo, Murdock, & Karnosh, 1987). On the other hand, a system that responds too quickly (before the user realizes the touch has been accepted) can also be confusing (Carroll, 1984).

Feedback, which is interrelated to response time, can be of different levels and types. Feedback is the return to the input of a part of the output. "A part of the output" implies that feedback may occur in different stages depending on the application and system capabilities. Consider the following scenario as a basis for defining the stages of feedback and illustrating the types of feedback.

> An expert computer system, using a touch device for interactive input, simulates human performance through complex modeling procedures. Much time is required to predict the performance, given the size of the data base. The operator needs the information as soon as it is computed, but the operator does not want to watch the monitor until it presents the result. Figure 5 is a hypothetical sequence of events that would occur when the operator touches the box labeled COMPUTE.

EVENT	STAGE OF FEEDBACK (FB)
1. TOUCH INPUT (touched COMPUTE box)	INITIAL FEEDBACK (main type is tactile; may also include visual and auditory)
2. Box that is touched lights up until touch is released.	INTERIM FEEDBACK (visual FB lets operator know a touch is detected)
3. "COMPUTING" appears on the screen.	INTERIM FEEDBACK (visual FB lets the operator know the touch was accepted and implemented)
4. Audible BEEP- just before the solution is generated.	INTERIM FEEDBACK (auditory FB alerts the operator, who has continued working and is not monitoring the screen, that the solution is now being generated)
5. Solution is presented on the screen.	RESPONSE FEEDBACK (final FB to the initial input)

TID RESPONSE TIME

SYSTEM RESPONSE TIME

Figure 5. Hypothetical sequence of events.

Figure 5 defines the three stages of feedback: initial, interim, and response. The types of feedback (tactile, visual, and auditory) are also indicated in this scenario. Tactile feedback occurs at the initial stage; the operator feels the finger or stylus pressing against the screen. Also included in the initial feedback may be visual and perhaps auditory feedback; the operator sees the finger or stylus stop moving when it contacts the screen and in some cases, may hear the contact. The interim and response stages normally include visual or auditory feedback. Visual feedback is usually achieved by reverse video, symbol flashing, or color change. Auditory feedback is usually in the form of a beep, and although it is an excellent cue for the user, it has irritated some users and especially third parties. Also, audible feedback can be masked by ambient noise in the environment.

Feedback depends on the system capabilities and the software programming expertise. Some touch systems may not have any interim feedback. If the system response time is very fast, the primary form of feedback will probably be the response feedback. Most TID systems will have an initial feedback; in IR systems, however, the stylus need not actually touch the screen to activate a touch, although it usually does. In systems where touch is recorded on stylus entrance and when the system response time is fast, there usually is not time or the need to provide interim feedback. If touch is recorded on stylus exit, it is imperative that some interim feedback be provided (usually visual, i.e., make the area being touched reverse video) to inform the operator of the accuracy of the touch, thus allowing for corrections.

Transmissivity and Image Clarity

TIDs in conjunction with a display may cause visual obstruction between the operator and the display. Transmissivity is the percentage of light output from the display when the TID is in place. LED and some SAW devices have 100% transmissivity because they do not obstruct the display, and some overlay systems have registered only 50% transmissivity. One manufacturer of a resistive overlay system, Elographics, Inc., claims that a transmissivity of 50% is barely noticeable to most users (Costlow, 1984). In addition to reduced transmissivity, some overlay-type TIDs affect the image clarity. The layers of material from which touch panel overlays are constructed may distort the video image making the screen harder to read. The optical degradation caused by overlays can hinder those applications requiring a clear, sharp, or colorful image (Logan, 1985). The application of a system is an important consideration when selecting the best TID based on transmissivity and image clarity.

Glare

Glare is produced by brightness within the visual field that is significantly greater than the luminance to which the eyes are adapted so as to cause annoyance, discomfort, or loss in visual performance and visibility (Sanders & McCormick, 1987). Reflected glare is the type encountered when operating computer systems. Some screens are coated with anti-glare substances; these coatings tend to show fingerprints, however. Some systems, often capacitance-type, rely on etched glass to control glare. Resistive TIDs are notably high glare systems. Middo, Murdock, and Karnosh (1987) claim the combination of glass and mylar overlays increases the glare and the problem is often worsened by translucent anti-glare coatings. LED and SAW devices, which do not have overlays, do not contribute to the system's glare, and any glare experienced is solely due to the display screen.

Spatial Resolution

The spatial resolution of TIDs refers to the capability of making distinguishable the parts of the display. In other words, resolution refers to the number of touch points per inch or how many X by Y points per screen size. For example, the resolution of a screen that is 10 inches by 10 inches might have 25 points per inch, or 250 X 250 touch points per screen. Discrete systems generally have low resolution (discrete number of defined touch points) and continuous systems have higher resolution (the number of points per inch is large enough that they are difficult to distinguish visibly). Resistive overlay TIDs are shown to have the best spatial resolution of the six types of TIDs discussed in this report. Fixed wire devices have the most limiting resolution capabilities. When considering the resolution of the touch device, it is important to focus clearly on the touch system's intended application. Even a small finger has a diameter of at least 0.25 inch. Therefore, since most applications, that is, control panels or function selection menus, use the finger as a stylus, finer resolution is not necessary (Carroll, 1984). Applications involving graphics may require the access of every pixel on the display; thus, the resolution of the touch device must be able to satisfy this requirement.

Visual resolution refers to the overall quality and discernability of the display. This measure includes the parameter of spatial resolution along with parameters such as luminance, contrast, and focus. This measure was used in a study by Schulze and Snyder (1983) to compare five TIDs.

Inter-Target Distance and Use of Dead Zones

The inter-target distance is an important operational consideration. Traditionally, targets that are to be accessed through touch should be separated according to the recommended guidelines for controls; separation of 0.25 to 0.50 inch is recommended (Van Cott & Kinkade, 1972). Maintaining the separation distance is easy when the targets are touch control keys in fixed positions on the display as pushbutton controls are fixed on a control panel. However, when targets are moving, such as aircraft on an air picture display, it may be difficult to access individual targets through touch. This difficulty is incurred because moving targets are often close together or on top of one another, thus violating the recommended control separation distance. Some TIDs can be programmed to deactivate the area between targets. These areas are called dead zones. It is recommended that whenever possible, each target should be surrounded with a dead zone where touches are not valid. This technique works well for touch zones that are stationary but has not been effectively applied to moving targets.

Touch Target Size

The appropriate size of a target depends on many factors such as resolution of the system, size of the display, typical viewing distance and angle, and the amount of data to be presented on the display. In general, the larger the touch target, the better. Carroll (1984) recommends that under normal viewing conditions, targets 0.5 inch square with 0.25-inch dead zones are sufficient. He recommends the targets for stressful conditions be 0.75 inch square, with a 0.5-inch dead zone. Gartner and Holzhausen in an evaluation of cockpit display and input using TIDs (cited in Pfauth & Priest, 1981), found that key activation times decreased significantly as switch sizes increased to 22 mm in diameter but stayed constant for sizes greater than 22 mm. Their recommendation for initial touch key size is a minimum size of 22 mm.

Symbol Shape and Color Coding

Symbol shape and color coding are important considerations when designing a system controlled by touch interaction. The recommendation of Carroll (1984) is to make targets regular in shape, make them symmetrical, equilateral, and predictable, unless the target is to be selected on the basis of shape. He also recommends that targets be uniform in color unless the choice is made on the basis of color. However, selection should never be based solely on the color of a target. It is recommended that color be used as redundant coding. The user should not be distracted by visual discriminations, such as color and shape differences, unless they are relevant to the current selection of options.

Z-Axis Performance

Some TID systems have Z-axis sensing capabilities and can assign required activation pressures to specific touch zones. Using this method, systems can safeguard against accidental touches.

Dialogue Development For TIDs

Touch interactive systems generally have been used in combination with the menu selection dialogue. The development of an effective menu hierarchy for use with TIDs will provide a powerful combination from which to approach the naive computer user (Pfauth & Priest, 1981). Using menu hierarchies effectively with TIDs can remove numerous layers of control menus necessary when operated by other traditional means. The task of the system designer is to use the menu hierarchy methods to create a user-friendly interface that reduces the complexity of interaction and training requirements. Touch technology simply provides a basis for designing a friendly and natural user interface (Carroll, 1984).

Work Place and Environmental Considerations

Temperature and Humidity Extremes

The different technologies of TIDs all operate under similar [illegible] temperature and humidity. They operate in temperatures ranging [illegible] to 50° Celsius and at noncondensing humidity levels up to [illegible]. According to the literature, resistive membrane devices are the most sensitive to humidity. However, some manufacturers rate the operational humidity level as comparable to other systems. Of the technologies [illegible] systems have the smallest operational range for [illegible].

Dirt, Grease, and Potential For Damage of TID Surface

Touch systems can be sensitive to dirt, grease, chemicals, and sharp objects. Touch overlay systems usually take most of the blame for these problems, but some of the problems affect non-overlay systems just as much if not more. A common misconception about overlay systems is that they become very dirty from fingerprints, very quickly. According to Logan (1985), most touch overlay screens have coatings to which grease will not adhere, and touch screens can go a long time between cleanings. In fact, most users never clean their screens, and most color monitors, which tend to attract dust to their surfaces, will actually be cleaner if a touch screen is used with them. Middo, Murdock, and Karnosh (1987) stated that anti-glare coatings tend to show fingerprints, but it is not clear if the coatings referred to by Logan (1985) are the anti-glare type. If smudges do occur, they can easily be cleaned with any glass cleaner. Generally, the computer screens of non-overlay systems probably need to be cleaned from dirt and grease just as often as the screens from overlay systems. Another problem is dust, which settles on all screens, but it is a serious problem for LED systems, especially those with color monitors, because it can eventually cause false readings. The top mylar layer of the resistive overlay system is particularly sensitive to chemicals. Resistive screens are also more sensitive to humidity as condensation can form between the layers. Resistive overlays may be scratched or punctured by hard or sharp probes and even when carefully used they will suffer from wear. Acoustic ranging devices are sensitive to dust, grease, and scratches which may cause invalid touches.

Angle and Reach Distance

System design partially depends on the environmental space constraints. The position of the touch panel in relation to the operator affects the degree of parallax because of the non-perpendicular line of sight. The position also affects the usefulness of the system. If the operator cannot see the panel clearly or cannot comfortably reach it because it is in a bad location, the panel is not being optimally used.

Vibration Effects

A considerable amount of research has demonstrated the effects of vibration on the tracking performance of seated subjects (Sanders & McCormick, 1987). Some generalizations can be made from this research. First, the effects of vibration depend somewhat on the difficulty of the task. Next, the effect of sinusoidal vibration on tracking tasks is not the same as the effect of random vibration. Further, vertical vibration is generally more debilitating than lateral or fore-aft vibration.

Biferno and Stanley (1983) stressed that although the technology exists to implement TIDs in helicopters, the effects of turbulence need to be studied. The input time, input accuracy, and equipment survivability should be considered and tested before implementing TIDs in an environment with turbulence. McDonnell Douglas Helicopter Company (MDHC) and the Human Engineering Laboratory (HEL) recently conducted an experiment to compare the effects of vibration on two different input methods--touch panel and bezel key. The data analysis is currently underway and the study is discussed further in the Applications and Research section of this report.

Electromagnetic Field Interference

When designing the touch system, the designer should consider the proximity of the TID to electromagnetic fields and protect the equipment with electromagnetic interference (EMI) shields. Capacitance systems are particularly sensitive to electromagnetic fields.

Summary

Manufacturers are aware of the operational considerations that affect TID performance and usability. Product bulletins, distributed by TID manufacturers, address most of the considerations by specifying the parameters, tolerances and operational capabilities of their system. Table 1 compares specifications and features of each touch technology. Manufacturers' printed specifications and, in some cases, verbal responses were used to complete the chart. Some of the technologies reflect the specifications of only one system; others are from a combination of manufactured products. For a complete listing of the technical brochures used in completing the table, please refer to the Appendix.

ADVANTAGES AND DISADVANTAGES OF TID TECHNOLOGIES

Each of the six touch technologies has intrinsic qualities viewed as advantages or disadvantages. The selection of a TID will be influenced by these qualities. Manufacturers are aware of the disadvantages of the technologies and some have taken extra steps to account for or alleviate the "bad" features. This report presents the characteristics of each technology which surfaced in the literature search. Any solutions to technological problems known to the author are also presented.

Table 1

COMPARING TOUCH PANEL TECHNOLOGIES

SELECTION FACTOR	FIXED WIRE	CAPACITIVE	RESISTIVE	INFRARED	SAW [5]	PRESSURE [7]
RESOLUTION	32-66 FIXED	100 X 100 - 256 X 256	1000 X 1000 - 4000 X 4000	.115" X .123"	.06" X .06"	256 X 256
Z AXIS	NO	YES [1]	NO	NO	YES	YES
TOUCH PROBE	ANY	CONDUCTIVE	SOFT	OPAQUE	SOFT STYLUS	ANY
RESPONSE TIME (TYPICAL)	NO INFO	20-50 ms	10-50 ms	50 ms	10-36 ms	NO INFO
TOUCH ACCURACY (TYPICAL)	NO INFO	1% OF SCREEN SIZE (SYSTEM)	.5% OF SCREEN SIZE (PANEL)	2% SYSTEM	.1% LINEARITY	96-98% OF THE TOUCHES ACCEPTED
PARALLAX	MINIMAL	MINIMAL	MINIMAL	NOTICEABLE	MINIMAL	MINIMAL
TRANSMISSIVITY	70-80%	85%	50-60%	100%	92%	N/A [4]
GLARE DUE TO TID	MEDIUM HIGH	MEDIUM	HIGH	NONE	MEDIUM	NONE
% OF DISPLAY THAT IS TOUCH INTERACTIVE	N/A	52-77%	56-80%	82-98%	90-100%	ANY PART OF THE SCREEN WITH CHARACTERS
EASE OF LATERAL MOVEMENT	INHIBITED	EASY	INHIBITED	EASY	EASY	EASY
OPERATIONAL TEMP RANGE	NO INFO	0-50° CELCIUS	0-50° CELCIUS	0-50° CELCIUS	0-50° C (comm) [2] -55-85° C (mil)	15.6-32.2 °C
OPERATIONAL HUMIDITY RANGE NON-CONDENSING	NO INFO	0-95%	0-90%	10-95%	0-95%	8-80%
ENVIRONMENTAL SENSITIVITY	NO INFO	MAGNETIC FIELDS, HUMIDITY & TEMP EXTREMES	HUMIDITY, DUST, CHEMICALS & SCRATCHES	AMBIENT LIGHT & DUST	SCRATCHES & [3] DIRT	HUMIDITY, TEMP EXTREMES AND VIBRATION
PANEL INSTALLATION	NO INFO	BEZEL MUST BE NON-CONDUCTIVE	MOUNTED IN SPACE BETWEEN PANEL & BEZEL	SPECIAL BEZEL NEEDED	MOUNTED IN SPACE BETWEEN PANEL & BEZEL	N/A [4]
CONTROLLER INSTALLATION	NO INFO	MOUNT INSIDE OF MONITOR IF ROOM	MOUNT INSIDE OF MONITOR IF ROOM	TYPICALLY MOUNT IN SPECIAL BEZEL	ON A 'PC' CIRCUIT CARD BLANK	N/A [4]
POWER (STD. [illegible])	NO INFO	+5V @ 350mA +/- 12V @ 150mA	+5V @ 600mA +/- 12V @ 100mA	+5V @ 2A +/- 12V @ 200mA	+5V @ 350mA +/- 12V @ 40mA	120 VAC, 1PHASE 3 WIRE, 60Hz
SERVICE & MAINTENANCE	SIMPLE REPAIRS	SIMPLE	SIMPLE MAY NEED TO REPLACE PANEL	MAY BE DIFF., HIGH # OF PARTS	REPAIRS DONE AT FACTORY	NO INFO
CERTIFICATIONS	NO INFO	YES	YES/LIMITED	YES/LIMITED	YES/LIMITED	YES/LIMITED
INTERFACES	NO INFO	RS 232, PARALLEL	RS-232, ANALOG & PARALLEL	RS 232	RS-232, SERIAL DATA LINK	RS-232C SERIAL & IEEE488 PARA
SOFTWARE VENDOR	NO INFO	YES	YES	YES	YES	YES
COST	NO INFO	$ [illegible]00 - $1500	$900 - $1500	$900 - $2000	$680 - $1250	$4900 - $7700 [6]

NOTES

1. The capacitive system, TekTouch™ by Tektronix, offers Z axis.
2. These temperature ranges are design goals for the Elographics SAW system.
3. The SAW system by Elographics has controlled for dirt and scratches; the system will perform if the conditions exist.
4. The IBM InfoWindow™ is marketed as a complete display/touch overlay system therefore these categories are not applicable (N/A).
5. Most of the specifications are for the Elographics system.
6. The estimate covers the entire IBM InfoWindow™ Package, not just the touch device.
7. Specifications are for the IBM InfoWindow™.

Fixed Wire Technology

Traditional fixed wire TIDs are a simple concept, but the resolution is very limited which leads to limited applications and usage. Unfortunately, a current manufacturer of the traditional device could not be found. Although Carroll Touch™ manufactures a device that is similar to the fixed wire device, it works in combination with a resistive coating technique. This device has a much finer resolution than the original fixed wire devices. Fixed wire overlays are shaped to match the shape of the display face thus limiting parallax. In a comparative study of TIDs by Schulze and Snyder (1983), users perceived that the fixed wire device (manufactured by Carroll Touch™) had high accuracy and was ranked best (of five) for both purchase and preference. The fixed wire device experienced one failure with repeated use; one of the wires broke. However, this device was repaired quickly and no further failures occurred. Additional drawbacks to the double overlay systems are the reduced transmissivity level and the inhibition of lateral movement because the top layer must firmly contact the bottom layer for detection to occur. The system is inexpensive when compared to the other technologies.

Capacitive Technology

Capacitive devices are single glass overlay designs that also reduce transmissivity, but not as severely as the double layer systems. Again, the overlay is curved to fit the display which limits parallax. The overlay's conductive coating has a high resistance to scratches, but if it is scratched, it may be destroyed. The coating repels chemicals and can be cleaned with glass cleaner. Some systems may have a problem with the moisture and static from operators' hands and may need to be calibrated often. Most systems require a conductive stylus; therefore, a pencil or gloved hand does not work. In the past, systems were overly sensitive to temperature and humidity, but most currently manufactured systems operate in temperature and humidity levels comparable to the other technologies. The single layer allows for ease of lateral movement as a light contact touch can be detected. One capacitive system called TekTouch™, developed by Tektronix, has Z-axis sensing capabilities (Middo, Murdock, & Karnosh, 1987). Most capacitive systems are low to medium cost systems. The comparative study by Schulze and Snyder (1983) used a device developed by Interaction Systems to represent the capacitive technology. Subjects experienced few errors when using the system. According to subjective ratings, the system was the third (of five tested) most useful and enjoyable system. The transmissivity of the system was second lowest, but helped the system to obtain the best (lowest) rating for amount of display noise. The capacitive device used for this experiment was extremely sensitive to static electricity. When a subject transferred static electricity to the panel through a touch, it sometimes coupled with panel current and the device failed.

Resistive Membrane Technology

Resistive technology offers very high resolution and the curved-to-fit overlays limit the amount of system parallax. The system consists of two layers that reduce the level of transmissivity and according to the literature, may increase the amount of glare. The top mylar layer is coated with a conductive substance. The mylar is sensitive to chemicals and is permanently damaged if punctured or scratched. The resolution and accuracy of the system degrades as the coating wears. The current systems are rated as operational in humidity levels comparable to other TIDs; however, if moisture forms between the layers, problems may arise. As mentioned before, double layer systems require the top layer to contact the bottom layer to register a selection and thus inhibit lateral movement or sliding across the touch panel. Failed units are not repairable and must be replaced, but they are generally inexpensive. Schulze and Snyder's 1983 comparative study used a device manufactured by Sierracin/Transflex Corporation to represent the resistive membrane technology. For this experiment, the resistive touch panel registered highest for error occurrence in all phases of the experiment. The device was tied for the lowest overall rating based on performance times and errors. The system was subjectively rated by the subjects and received average to good ratings for legibility and usability. It received low ratings for preference and purchase. It was noted that this system was prone to drift and misalignment through repeated use, leading to misreadings of touches and an increase in errors.

LED (Infrared) Technology

Infrared (IR) devices are completely transmissive because the device is not an overlay. In the past, considerable attention was drawn to IR problems of limited resolution and parallax. Today, the primary manufacturer of IR devices, Carroll Touch™, claims the resolution of the touch device is as fine as the display's resolution. Currently, researchers have proposed and developed several corrective procedures to reduce parallax, but according to Logan (1985), most of the corrective procedures only reduce the amount of parallax by 50%. Carroll Touch™ minimizes parallax by curving the rows of emitter-detectors according to the screen's contour. IR touch systems do not add glare to the display screen, and scratches, dirt, and oil on the display surface do not cause malfunctions (Carroll, 1984). The IR system, if not properly programmed, may be triggered by dust, strong ambient light, and even flying insects. Any such occurrences, however, are usually rare. The lenses on the emitters and receivers need to be kept relatively clean and free from dust, but since they are behind a plastic bezel, the system may operate for many hours before cleaning is necessary. In comparison to other technologies, IR systems are subject to few environmental constraints. Middo, Murdock, and Karnosh (1987) stated that IR devices are sensitive to vibration; however, in a recent experiment by MDHC and HEL, a Carroll Touch™ screen was operational for many trials in vibration levels ranging from 3 to 100 Hz. Although IR devices have a high number of parts and are sometimes difficult to repair, the units can usually be repaired by the consumer. The units are activated by an opaque stylus. The stylus must enter or exit perpendicular to the matrix of beams. The unit requires a special bezel to house the emitters and receivers and requires extra space in front of the display. In the study by Schulze and Snyder (1983), a Carroll Touch™ device was used for the IR category. Performance of the device was very good. The system had a high accuracy rate and the trial times were lower or comparable to the times of the other devices. The authors noted that parallax was not a problem for the experiment because the active touch areas were not on the periphery of the display. Overall, the IR-LED technology device tied with the fixed wire technology device as the best system, based on operator performance. The subjective comments indicated users felt the IR system was too sensitive. IR received the lowest subjective rating for utility. The system tied for most dependable and rated highest for visual resolution. IR had the most display noise (surface luminous variation) which is attributed to the high transmissivity. The system received high rankings for purchase and preference.

Another representative of LED technology is developed by ITW Entrex. As previously described, the system uses one light source on a rotating motor. The design has the advantages of a smaller parts count (fewer LEDs and detectors), a decreased cost and a finer resolution as compared to the matrix IR system. The major problem with the system is the unreliability of the electromechanical motor. This system suffers from the same problems of parallax and non-contact triggering (dust, insects, etc.) as the matrix system. The durability of the system is decreased because the motor may burn out and require replacement.

Surface Acoustic Wave (SAW) Technology

SAW technology has undergone many improvements in the past few years. This technology features Z-axis sensing capabilities (some systems) along with high resolution in the X-Y directions. These systems can be very sensitive to dirt, grease, and scratches, which cause echoes contributing to noise and risking false touch detections. Elographics has manufactured a SAW device that uses a reflective array approach originally developed at Zenith in 1986. The system uses a reference wave form to compare the signal level of the screen. The reference wave form is updated whenever panel contamination is detected. Panel contamination includes dirt, grease, scratches, and anything else that is stationary on the display surface for 2.5 seconds or more. Dirt and foreign materials only affect the reference wave form until the screen is cleaned; scratches become part of the permanent "signature" of the screen and are accounted for each time the screen is memorized (Elographics, 1988). The system also has the ability to adjust to changing conditions such as temperature and humidity. In regard to Z-axis sensing, this system can discriminate as many as 16 levels of applied touch pressure.

Another SAW device (no Z-axis), developed by TSD Display Products, has been in use for several years. Accumulated dirt from finger touches will sometimes cause unwanted responses, but customer reports indicate that cleaning of the screen is normally necessary only once or twice a week. The glass overlay in this system must not be scratched because it will produce a permanent echo which may cause unwanted responses. SAW devices have high resolution and can sense light touches (good lateral movement). The systems have fewer parts than most TID systems. The acoustic ranging device, used in the previously mentioned experiment by Schulze and Snyder, was manufactured by TSD Display Products. The device had the second highest transmissivity value and was second highest for spatial resolution. The device's overall rank was last, based on operator performance. The system received medium to low subjective ratings for usability, legibility, enjoyment of use, preference, and purchase; yet, it was one of the most dependable units. Users' comments indicated they felt the device was insensitive.

Pressure-Sensitive Devices

Pressure-sensitive devices were first conceived in 1976 by the Army Research Institute. The researchers developed a pressure-sensitive device (which used strain gauges) and evaluated the characteristics of pressure-sensitive input. Some general conclusions surfaced about the system design. The system was very sensitive to vibrations, higher touch pressures, and temperature changes. A current manufacturer of this type of system could not be found. Another system, however, which uses piezoelectric force transducer crystal technology, was found. This device, called the InfoWindow™, was developed by IBM. It is a compact unit with a high resolution color display including a built-in touch-sensitive screen. The system has a built-in calibration program that nearly eliminates any drift, and the system has a high accuracy and reliability rate according to the published specifications. Its resolution capabilities are comparable to the other technologies and the image quality is very good because no additional overlays are necessary as the touch system is built into the display screen. The system's operational temperature and humidity ranges are smaller than the other technologies, but it is not clear which of the system components drives these limitations. The major disadvantage of the system, as seen by the author, is that the touch system is not manufactured separately from the display unit.

Summary

When choosing a TID, the advantages and disadvantages of each technology will determine the suitability of each technology for given applications. Table 2 summarizes the advantages and disadvantages, as indicated in the literature, for each technology.

APPLICATIONS AND RESEARCH

Several research experiments investigating applications of TIDs surfaced in the literature review. Discussed below are five of the experiments that related most directly to the operational and environmental concerns of TIDs.

Vibration Experiment

This experiment was an evaluation of touch and bezel keys as operator input methods in a helicopter environment. This research experiment was conducted at Aberdeen Proving Ground, Maryland, as a joint effort between MDHC and HEL. MDHC recognized that touch panels may be effectively used in helicopter missions; however, the literature did not support or deny the effectiveness of touch panels in a dynamic environment. The experiment focused on the effects of various helicopter flight maneuvers and associated vibration levels on operator response time, input time, and error rate using touch and bezel keys as input methods. The experiment tested touch locations on the perimeter of the display corresponding one to one to the bezel keys. Data analysis was completed and a report is pending from MDHC.

Method of Touch Implementation Experiment

This research effort, conducted at Westinghouse Electric Corporation, evaluated seven methods of touch screen entry. The researcher was concerned that the selection of an item on the face of a touch screen sets in motion a series of pre-programmed events, often offering no opportunity for user input or correction (Murphy, 1986). Murphy felt that if an error recovery process were incorporated in the TID design, two types of errors could be controlled: those that occur as a result of mispointing and those that occur as a result of errors in procedures and are recognized as such by the user before the command or data sequence is transmitted to the system. Based on the notion that allowance for error recovery may alleviate the execution of some incorrect touches, Murphy devised six touch methods that separated task selection from execution. The seventh method used a single touch to accomplish both, not allowing for any corrective action. The seven methods were compared on the basis of error rate and time required to select and execute a displayed item, using an infrared TID. Fifteen subjects were tested with each of the seven methods. In general, the results confirmed that the single touch method was the fastest and four of the other methods were equally as fast (no statistical difference). Further, based on statistical testing, the probability of error occurrence was the same for

Table 2

Advantages and Disadvantages of Touch Interactive Devices (TIDs)

TID	Advantages	Disadvantages
Fixed Wire	Simple concept Users perceive high accuracy and good responsiveness Little parallax Repeals chemicals Inexpensive	Limited resolution Touch locations fixed Overlays decrease transmissivity Few manufacturers Lateral movement inhibited
Capacitive	Little parallax Repels chemicals High resistance to scratches Good lateral movement Z-axis (one system) Medium cost	Capacitive material decreases transmissivity Potential problem from moisture and state of user's hands Scratches may destroy capacitive layer Pencil or gloved hand may not work Some systems sensitive to temperature and humidity Some systems may need continuous calibration
Resistive Membrane	Potential for very high resolution Little parallax Relatively inexpensive	Conductive material decreases transmissivity Reflective overlays (Mylar or glass) may increase glare Vulnerable to vandalism, punctures, and scratches Mylar sensitive to chemicals Some systems sensitive to humidity Failed units are not repairable Resolution degrades as coating wears Lateral movement inhibited

(continued on next page)

Table 2 (continued)

TID	Advantages	Disadvantages
LED	100% transmissivity Can use nonglare glass Few environmental constraints Scratches, dirt, and oil do not cause malfunctions Failed units can be repaired by customer Resolution as fine as the display Ease of lateral movement	Higher cost Excessive dust can cause misreadings Potential parallax problem Sensitive to strong ambient light Requires more space in front of display Stylus must enter or exit perpendicular to the screen High number of parts Some users feel it is too sensitive
SAW	Z-axis capability High resolution Good lateral movement Good linearity One system can adjust to changing conditions of temperature and humidity Medium cost	Sensitive to dirt and grease (may cause invalid touches in some systems) Some users feel some systems are not sensitive enough Scratches on glass cause echoes contributing to background noise in some systems
Pressure Sensitive	One system has good calibration and little draft High accuracy and reliability High resolution Good image quality Some systems have Z-axis	Some systems are sensitive to vibration, temperature, and humidity One touch system is not manufactured separately but is part of a display unit

... the seven methods including the single touch method. ... concluded that the touch method should be based on the cost of an error. When cost is low, the single touch method is perfectly adequate, but for systems when the cost of an input or command is high, a multiple touch method must be used to give the operator the opportunity to correct the error.

Underlying Behavioral Parameters of the Operation of TIDs

Beringer and Peterson (1985) recognized that although TIDs have exhibited a number of advantages in relatively low resolution applications, the requirements for high resolution touch input must take into account the inherent biases and limitations of the operator. In Study I, performance biases in the use of an infrared TID were examined with the input surface at various declinations. The results indicated a general bias to touch low and to the right of the intended target (for right-handed subjects). The low bias increased with increasing display declination. In the second part of Study I, simple models were developed in an attempt to reduce bias. Results showed bias was reduced more effectively when the models were derived from individual performance trials than when derived from populational behavior (averages). The second study examined effects of handedness and the effects of feedback on training paradigms. Results showed that right-handed subjects had a bias to touch to the right of the target; left-handed bias was exactly the opposite. The report discusses the feasibility of training as a viable alternative to control performance biases. The preliminary results revealed that several subjects adopted rhythmic response patterns. The trend across groups was toward longer response times with feedback.

Comparative Evaluation of Five Touch Entry Devices

An experiment comparing five touch entry devices was sponsored by AMP, Inc., and conducted at Virginia Polytechnic Institute by Schulze and Snyder (1983). The experiment was conducted in four phases. Phase I was designed to evaluate the physical display quality (referred to as visual resolution in this report) for each system. Phase II consisted of experiments designed to assess operator performance on the equipment configurations. Subjective assessments of the configurations were collected in Phase III. Phase IV involved correlational analyses conducted in an attempt to relate phases I, II, and III to each other. Each touch entry device was paired with two separate monitors allowing for 10 test configurations. Highlights of the results for each device were presented in the Advantages and Disadvantages section of this report.

Controller Evaluation of a Touch Input Air Traffic Data System

The following experiment by Stammers and Bird (1980) was an evaluation of a system for data transfer and display of airport air traffic control (ATC) information. The computer-based system handled data that were normally used for ATC at Heathrow Airport in London, England. The system displayed the controller's data on a single screen. Data transfer and modification was enabled via a touch sensitive surface. The touch technology employed was light-emitting diodes or infrared. The primary objective was to examine the opinions and attitudes of controllers. The study simulated normal operations and the main source of data collected were the subjective questionnaires which were administered after completion of the exercises. Some of the simulations were video and sound taped for documenting controller interaction with the system. In general, the following are conclusions and recommendations made by the authors based on the users' comments and system ratings:

1. The touch input system is a highly acceptable one from the user's point of view, its method of use being quickly learned. There is a high compatibility between display and control and ease of use.

2. Errors were still made with the touch input system, however, and efforts need to be directed toward providing better feedback from the device to the user. In addition, special efforts need to be made in training toward reducing error.

3. While the touch system was commented upon favorably, it was not evaluated against other alternatives for ATC.

4. The system must have a rapid rate of change following human input. An unexpected finding in this study suggests that noticeable delays can be disruptive.

5. It is important to give adjustment controls for factors such as distance, angle, brightness, and contrast, to encompass individual differences and preferences and to cope with the various ambient light conditions that may be encountered.

6. System design must further consider the method of "logical progression" so as to minimize the number of touches required to use the system.

CONCLUSIONS

Currently, the most prevalent TIDs are resistive overlays, IR beams, and capacitive overlays. Surface acoustic wave and pressure-sensitive overlays have unique capabilities of accurately sensing in three dimensions. Both technologies have undergone several advances in recent years and are very viable competitors. Fixed wire TIDs, which are the root of touch technology, have been nearly replaced by the other five technologies which have gre ter capacities and abilities. Each technology has its own advantages and disadvantages which should be closely considered when choosing a system.

The consensus of the literature is that TIDs

provide a direct visual-to-tactile control,
usually require minimal user training,
are highly accepted by users,
have minimal eye-hand coordination problems,
may eliminate need for keyboard given space constraints, and
provide a software flexible interface.

Some perceived disadvantages of TIDs are they

are not well suited for alphanumeric data entry,
are sometimes costly,
require more programmer time,
have various problems such as parallax and glare that affect performance,
create physical fatigue from reaching to the screen,
block vision when the stylus touches the screen.

RECOMMENDATIONS FOR FUTURE RESEARCH

Based on the information presented in this report, it is apparent that touch interactive devices are effective control interfaces for many applications; however, several factors still need to be researched to achieve maximum operator performance. The following are recommended areas requiring further research:

1. The types of feedback best suited for TIDs.

2. The effectiveness of TIDs in finer graphics applications, specifically, resolution, minimum stylus diameter, transmissivity, and image clarity.

3. Effective target size and target separation zones for TIDs.

4. Use of color coding for symbols on TIDs.

5. Z-axis capabilities and effective applications.

6. Menu hierarchies and dialogue development for TIDs.

7. Angle and reach distance preferences for TIDs.

8. Effects of vibration on TIDs. Compare performance of different touch technologies touching targets located randomly on the entire screen.

9. Performance of different technologies (TID technologies as well as other input methods) under various task loading.

10. Performance of different technologies when operator is wearing flight or NBC gloves.

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APPENDIX

MANUFACTURERS' REFERENCES

MANUFACTURERS' REFERENCES

Carroll Touch

Add-Touch™ Products for CRT Monitors
Specifications Sheet CTFS1-7/85

Carroll Touch Product List
Document Number CTPL-05/88

Available from:
P.O. Box 1309
Round Rock, TX 78680

Detector Electronics Corporation

DET TRONICS Specification Data
Document Number 90-1019-05, 8/84

Available from:
6901 West 110th Street
Minneapolis, MN 55438

Elographics, Inc.

E274 Touch Screen Specifications

Surface Acoustic Wave Specifications

Available from:
105 Randolph Road
Oak Ridge, TN 37830

Intech Systems Incorporated

The Intech Touch Screen- A Human Approach to Data Access
Document Number 82-1100 9/85

Available from:
6901 West 110th Street
Minneapolis, MN 55438

International Business Machines Corporation

IBM InfoWindow™ System
Document Number G580-0852-00

Available from:
Department CCP
900 King Street
Rye Brook, NY 10573

MicroTouch Systems Inc.

MicroTouch™ Kits
Specifications Sheet

Available from:
Ten State Street
Woburn, MA 01801

TSD Display Products

Touch Screen Digitizer Models: TSD-12A/15A
TSD-12B/15B

Available from:
35 Orville Drive
Bohemia, NY 11716